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CHAIN SAMPLING AS USED IN ARMOR ACCEPTANCE TESTING

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U.S. ARMY LABORATORY COMMAND

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The Probability and Statistics Branch of the Ballistic Research Laboratory was asked to develop a procedure of acceptance testing for armor packages. Because the available sample sizes were extremely small, we were unable to identify a sampling plan directly applicable to this problem. Accordingly, a new procedure has been devised by adapting an existing technique, known as chain sampling, to both the attribute portion (structural integrity) and the variable portion (penetration depth) of the acceptance testing process. Operating characteristic curves and average sample number curves are presented for this procedure, and suggestions are made concerning the simultaneous use of quality control charts.

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I. INTRODUCTION

In most cases a consumer's decision concerning whether or not to accept a manufactured product is based on an examination of a sample from that product. When General Mills introduces a new pre-sweetened breakfast cereal, they spend millions of dollars in advertisement costs with the hope that the consumer will sample it. Here, the consumer considers the entire supply of this new cereal as a single manufactured lot, to be accepted or rejected. Product acceptance, in this case, corresponds to the consumer purchasing more boxes of the new cereal.

This is merely an everyday example of what is known as acceptance sampling, that is, various techniques which allow for discrimination between an acceptable product and an unacceptable one. Sampling may be based on an attribute criterion, a variable criterion, or some combination of these. In our example the consumer may judge the sweetness of the cereal as satisfactory or excessive (attribute), or he may measure the time in milk before the cereal becomes soggy (variable). Sampling by attributes is a dichotomous situation in that, based on a particular attribute, each item is either defective or non-defective; rejection occurs if there is a high percentage of defectives in the sample. Sampling by variables establishes an acceptable level of a particular variable, and rejection occurs if its sample value crosses the acceptable threshold. Of course, in our example of a box of cereal, the sample size was one. Generally, this will not be the case; but occasionally, for one reason or another, the consumer is forced to make a decision based upon a very small sample size.

Because decisions are made from samples, there is some risk of error, either the error of accepting a bad product or the error of rejecting a good product. The amount of protection desired against such risks can be specified. The Acceptable Process Level (APL) is a high-quality level that should be accepted $100(1-\alpha)\%$ of the time; α is thus defined to be the producer's risk. The Rejectable Process Level (RPL) is a low-quality level that should be accepted only $100(\beta)\%$ of the time; β is thus defined to be the consumer's risk. Unfortunately, these error factors vary inversely; that is, as the consumer's risk grows, the producer's risk diminishes and vice versa. The Operating Characteristic (OC) curve is an important part of any acceptance sampling plan, since it provides a graphical display of the probability of accepting a product versus the value of the particular parameter being inspected. The OC curve is a function of APL, RPL, α, and β, as well as sample size. Given a particular acceptance sampling plan, the OC curve depicts the associated error risks and demonstrates the relationship among all of the variables.

The US Army Ballistic Research Laboratory (BRL) has developed an acceptance sampling plan for armor packages. This plan was briefed to the Project Manager M1A1 on 14 April 1988 at Aberdeen Proving Ground, Maryland. Its general structure was accepted with the guidance that the processes would be officially adopted pending some refinements.

II. CHAIN SAMPLING

Numerous sampling techniques exist, each with special properties that make it applicable to particular situations. Sampling plans reviewed in the literature required sample sizes much larger than those feasible for armor testing. In our case extremely small sample sizes were warranted due to the expense of both the armor and the testing procedure, augmented by the destructive nature of the test itself. Accordingly, we have devised a new procedure by adapting an existing technique, chain sampling, for use in this project.

Chain sampling is particularly appropriate for small samples because it uses information over the past history of production lots. Even with small samples, it is possible to accept a marginal lot provided that a given number of lots immediately preceding (i.e., the chain) were acceptable. When a consumer uses an expendable product such as the breakfast cereal in our previous example, he utilizes chain sampling in his decision of whether or not to subsequently purchase the same product. If the first or second box he buys is unacceptable, he will probably discard the product forever. However, if the tenth box is unacceptable, he might continue with one more purchase of the same cereal taking into consideration its past history of nine boxes of acceptable quality.

An advantage of chain sampling is its automatic incorporation of reduced or tightened inspection procedures when applicable. That is, as quality remains acceptable over a period of time and our confidence grows, the sample size is reduced (or, more accurately, samples are taken less frequently). If quality becomes marginal, inspection is tightened by taking samples more frequently. When quality diminishes to the point where a production lot must be rejected, the production process is stopped and necessary adjustments and corrections are made. At that point a new chain begins and progresses as before.

Certain assumptions must be accepted before chain sampling is considered as a sampling technique. In particular, production should be a steady, continuous process in which lots are tested in the order of their production. Also, there should be confidence in the supplier to the extent that lots are expected to be of essentially the same quality. Generally, a fixed sample size will be maintained with the investigator taking more or fewer samples as tightened or reduced inspection is dictated.

III. ACCEPTANCE SAMPLING PLAN

The armor packages include both a right-side package and a left-side package, which are designated as one set. One month's production is considered to be a production lot. Every month we continue testing one set at a time until a decision can be made about that production lot. For a given set, one shot is fired into each package; and, if the impact point on the target permits, a second shot follows. In each of the first three months, a total of at least four shots is required in order to make a decision concerning that month's production. This provides additional confidence during the early stages of the plan. There are two portions of the acceptance sampling plan. The first is structural integrity, handled using attribute methods; the second is depth of penetration of a particular round fired into the armor, handled using variable techniques. For both portions, decisions concerning a production lot should be based upon the data from all available shots on that lot.

A combined chain sampling plan was proposed. The maximum length of the chain was fixed at eight, meaning that after the chain has been established, we will consider the current set along with the seven immediately preceding. While the chain is growing, there is an area between the criteria for acceptance and rejection in which we can make no decision. At least one set will be tested each month; but if no decision can be made, tightened inspection will dictate the examination of additional sets, possibly up to a maximum of eight. Table 1 shows the relationships among months, sets, and shots for this particular procedure. Note that the maximum number of sets and, hence, the maximum number of shots decrease over time as the chain is being formed. Following the third month and the concurrent drop in the minimum number of shots, then when the chain is at its full length (definitely by the eighth month), one set and at most four shots are all that is required in order to make a decision for each subsequent production lot.

A rejection in either the structural integrity or the penetration depth will result in overall rejection of the production lot. In that case, production is stopped; adjustments and corrections are made; and testing resumes with the construction of a new chain. If neither measure results in a rejection but at least one falls within the no-decision region, another set should be examined and both categories re-evaluated using the additional data.

A. Acceptance Sampling by Attributes

Projectiles are fired at these sets, which are then inspected for structural integrity. With attribute sampling, only two outcomes are possible. The structural integrity, after testing, is assessed to be either adequate or inadequate, regardless of the number of shots. Any decision to either accept or reject a lot is based on the number of defective packages in the sample being considered.

Chain sampling is employed in this attribute sampling plan. Results from the most recent eight sets are considered when making decisions regarding a lot. A lot can be either accepted or rejected at any time (except for one case discussed in the following paragraph). In the early stages of sampling there is also an area in between acceptance and rejection where no decision is rendered immediately but sampling is continued. After a chain reaches its full length of eight sets, a decision to accept or reject is made immediately.

In the sampling plan, a safeguard is built in to prevent rejection of a good lot after only one set. If there are no defectives in the first set, the lot is accepted. Otherwise, no decision is made. Subsequently, rejection would occur only when there were three or more failures in the most recent eight sets. Table 2 shows the decision rules for a chain building to a maximum length of eight.

The OC curve for this plan is depicted in Figure 1. It provides the probabilities of lot acceptance as a function of the defective rate, the defective rate being defined as the true proportion of defective packages in any given manufactured lot. For our chain sampling plan, where the sample size is not fixed, the Average Sample Number (ASN) curve becomes important. It is shown in Figure 2 and indicates the expected number of sets necessary to arrive at a decision, once again as a function of the defective rate. Notice that the number of sets equals two at the worst defective rate. In this case the chain would be restarted continuously, and our decision rules (Table 2) dictate that we cannot reject on the first set.

TABLE 1. Relationships Among Parameters in Chain Sampling Procedure

Month	Required Sets Minimum	Required Sets Maximum	Required Shots Minimum	Required Shots Maximum
1	1	8	4	32
2	1	7	4	28
3	1	6	4	24
4	1	5	2	20
5	1	4	2	16
6	1	3	2	12
7	1	2	2	8
8	1	1	2	4
9	1	1	2	4
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
k	1	1	2	4

TABLE 2. Decision Rules for Attribute Portion of Chain Sampling Procedure.

SET NUMBER	DECISION RULES: ACCEPT	REJECT	NO DECISION
1	$f_1 = 0$	----	$f_1 \geq 1$
2	$\sum_{i=1}^{2} f_i = 0$	$\sum_{i=1}^{2} f_i \geq 3$	$1 \leq \sum_{i=1}^{2} f_i \leq 2$
. . .			
5	$\sum_{i=1}^{5} f_i = 0$	$\sum_{i=1}^{5} f_i \geq 3$	$1 \leq \sum_{i=1}^{5} f_i \leq 2$
6	$\sum_{i=1}^{6} f_i \leq 1$	$\sum_{i=1}^{6} f_i \geq 3$	$\sum_{i=1}^{6} f_i = 2$
7	$\sum_{i=1}^{7} f_i \leq 1$	$\sum_{i=1}^{7} f_i \geq 3$	$\sum_{i=1}^{7} f_i = 2$
8	$\sum_{i=1}^{8} f_i \leq 2$	$\sum_{i=1}^{8} f_i \geq 3$	----
9	$\sum_{i=2}^{9} f_i \leq 2$	$\sum_{i=2}^{9} f_i \geq 3$	----
. . .			
k	$\sum_{i=k-7}^{k} f_i \leq 2$	$\sum_{i=k-7}^{k} f_i \geq 3$	----

f_i = number of failures in set i

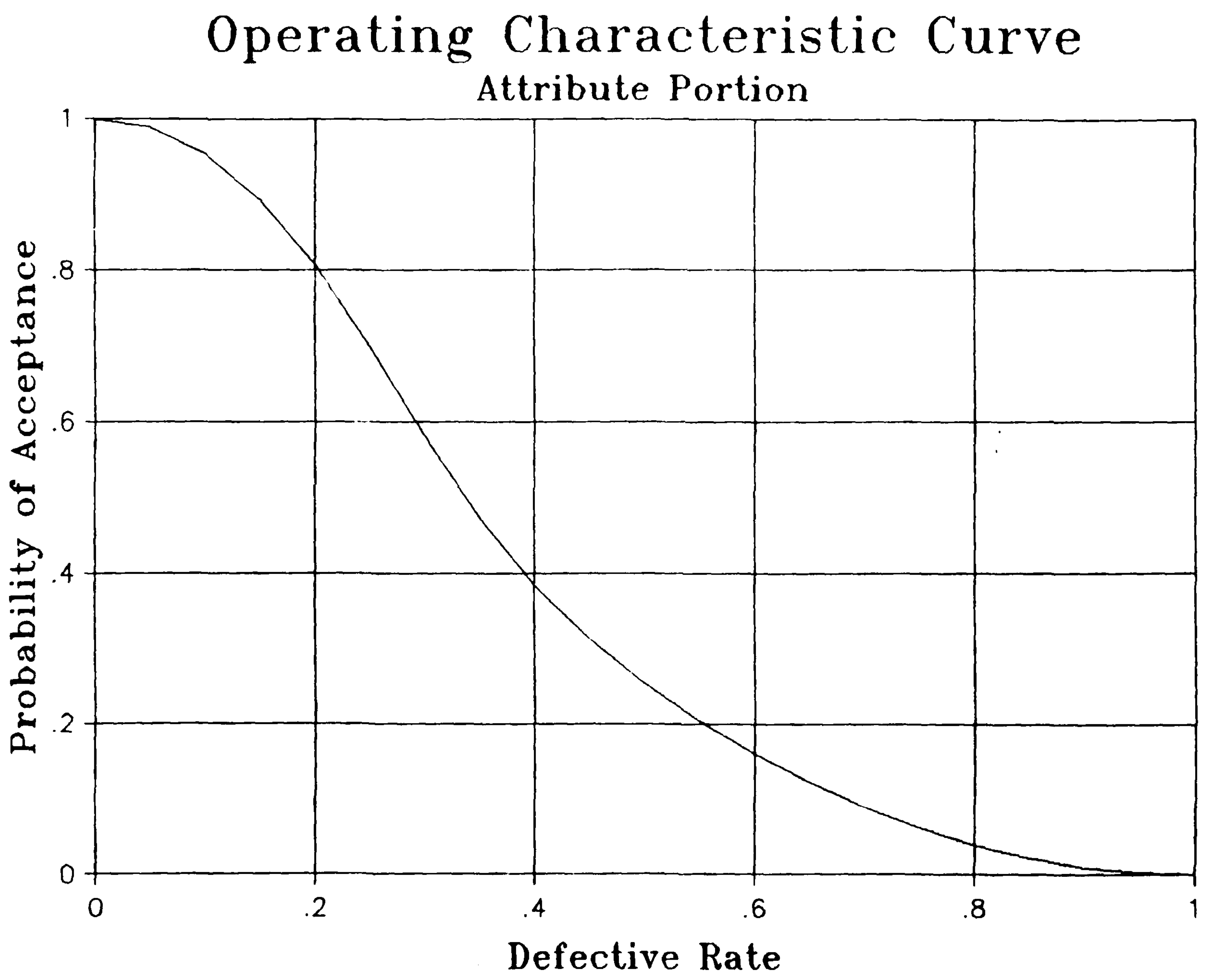

FIGURE 1. OC Curve for Attribute Portion of Chain Sampling Procedure.

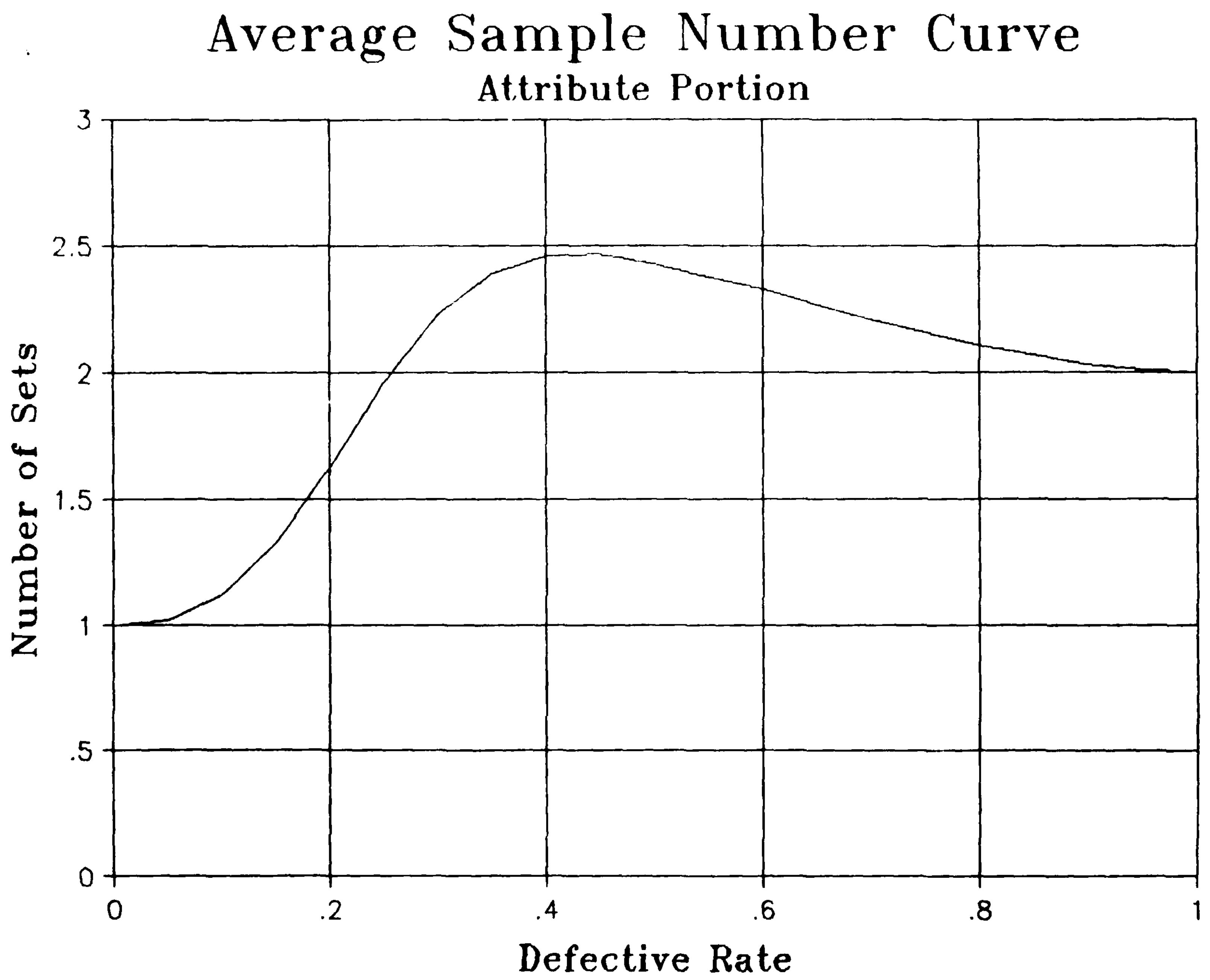

FIGURE 2. ASN Curve for Attribute Portion of Chain Sampling Procedure.

Figure 1 and Figure 2 were both computed analytically. As an example of these figures, suppose we have a lot with a defective rate of 0.1. Then the average sample size is 1.12 sets, and the probability that the resulting decision would be to accept the lot is 0.95. If the probabilities from the OC curve are deemed to be unsatisfactory, a different plan providing more satisfactory levels could be developed by varying the maximum chain length or modifying the decision rules. Of course, such modifications would alter the ASN curve as well. The OC curve and the ASN curve have been presented in their entirety, although, in a practical sense, expected defective rates are generally less than 0.2.

B. Acceptance Sampling by Variables

When primary interest is in a process level rather than a defective rate, sampling by variables is the proper procedure. For the armor packages, depth of penetration for a particular munition was the process level of interest. When variable sampling plans are established, two major assumptions must be satisfied: first, the distribution of the variable of interest must be known; and second, a good estimate of its standard deviation must be available.

In our particular problem there were 22 baseline shots from which we were to determine a distribution and estimate its standard deviation, as well as establish acceptable and rejectable process levels (APL & RPL). The 22 shots had a mean (X_b) of 5mm with a standard deviation (s_b) of 30mm. The data had been transformed, allowing for both positive and negative penetration values. When plotted, the data appeared normally distributed; and, indeed, the hypothesis of normality could not be rejected using statistical goodness-of-fit tests. The APL was established at 20mm (1/2 baseline standard deviation from the baseline mean) and the RPL was set at 80mm (2 1/2 baseline standard deviations from the baseline mean). α, the probability of rejecting at the APL, was set at 0.05; and β, the probability of accepting at the RPL, was allowed to vary with the sample size -- for a sample of size four, β would be approximately equal to 0.10.

As in the attribute case, a set consists of a right-side package and a left-side package. For each set an attempt will be made to fire a second round into each package. Because this might not always be possible, due primarily to discrepancies between the aim point and the hit location, each set can result in either two, three, or four data points, depending on whether or not both shots on each package are considered to be good hits. It is important that during the first three months, while the chain is being formed, at least four shots are available upon which to make a decision. Table 3 outlines the decision rules for the variable sampling plan. Like the attribute sampling plan, it incorporates chain sampling with a maximum length of eight sets. The plan will not reject based on the first two samples, and it has a region of no decision until the chain reaches its full length. In this table, $\bar{X}$ represents the mean penetration depth for all shots currently considered, s represents the standard deviation of this sample, n is the total number of shots used in computing $\bar{X}$, and t_{95} represents the 95th percentile of the t-distribution for the appropriate degrees of freedom (n-1). Thus, n can vary from 2 to 32 depending upon the length of the chain and the number of shots available on each package from the armor set.

TABLE 3. Decision Rules for Variable Portion of Chain Sampling Procedure.

SET NUMBER	DECISION RULES: ACCEPT *	REJECT *	NO DECISION
1 ($n < 4$)	---	---	ALL
1 ($n = 4$)	$\frac{\bar{X} - APL}{s/\sqrt{n}} \leq t_{.95}$	---	$\frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.95}$
2 (combine with 1)	$\frac{\bar{X} - APL}{s/\sqrt{n}} \leq t_{.95}$	---	$\frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.95}$
3 (combine with 1,2)	$\frac{\bar{X} - APL}{s/\sqrt{n}} \leq t_{.95}$	$\frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.99}$	$t_{.99} \geq \frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.95}$
⋮			
7 (combine with 1-6)	$\frac{\bar{X} - APL}{s/\sqrt{n}} \leq t_{.95}$	$\frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.99}$	$t_{.99} \geq \frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.95}$
8 (combine with 1-7)	$\frac{\bar{X} - APL}{s/\sqrt{n}} \leq t_{.95}$	$\frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.95}$	---
9 (combine with 2-8)	$\frac{\bar{X} - APL}{s/\sqrt{n}} \leq t_{.95}$	$\frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.95}$	---
⋮			
k (combine with (k-7) - (k-1))	$\frac{\bar{X} - APL}{s/\sqrt{n}} \leq t_{.95}$	$\frac{\bar{X} - APL}{s/\sqrt{n}} > t_{.95}$	---

* At least four shots are required in each of the first three months; otherwise, regard as "No Decision".

Figure 3 depicts the OC curve assuming four shots on every set. The abscissa value, D, represents a multiple of s_b from $\bar{X}_b$; thus, the numbers in parentheses are the mean penetration depths in millimeters. Note that the probability of accepting at the APL is greater than 0.95 (1-α). This results from the region of no decision prior to the chain reaching its full length. Some lots for which we could make no early decision will eventually be accepted, thereby inflating the probability at the APL. Because the probability of accepting at the RPL would be too high for two or three shots per set, the procedure will not allow early lot acceptance at these small sample sizes (see Table 3). Table 4 provides the values for the t-statistic for (1-α)-levels of 0.99 and 0.95 and degrees of freedom from 3 to 31.

Figure 4 shows the ASN curve as a function of D, once again assuming four shots on every set. Here, the number of sets approaches three as D grows large. As in the attribute case, the values (now, mean penetration depth) become so bad that the chain is restarted continuously; and the decision rules for the variable portion (Table 3) dictate that we cannot reject on either of the first two sets. Figure 3 and Figure 4 were both derived from a Monte-Carlo simulation study incorporating 10,000 replications.

Because the probability of accepting a lot in the attribute sense is independent of the probability of accepting a lot in the variable sense, we can calulate an overall OC curve merely by multiplying the respective probabilities associated with any given defective rate and any given mean penetration depth. An overall ASN curve can be approximated by considering the number of sets required for such defective rates and the number of sets required for such mean penetration depths and then choosing the maximum of those two values.

C. Quality Control Charts

Variations in the manufacturing process are either random or assignable. A process is "in control" when only random variations are present. Assignable variations, if uncorrected, may eventually result in rejection of a manufactured lot. However, they can often be identified through the use of quality control charts.

A quality control chart is a graphical comparison of test data with some previously computed control limits. The most common quality control chart is the Shewhart chart, named for its originator, Dr. Walter A. Shewhart. Figure 5 is a Shewhart control chart for mean penetration depth, the variable of interest in our armor package acceptance sampling plan. The baseline mean (5mm) is the central line with an upper control limit equal to 50mm, which, for a sample of size four, represents three sample standard deviations from this mean. If we were concerned about extremely low penetration depths, we would incorporate a lower control limit as well. Assuming a normal distribution with parameters equal to those of the baseline data implies that if only random variations are present, 99.87% of the time the mean penetration depth of the sample will fall below the upper control limit. This leaves a false-alarm frequency of less than 1% (0.13%) - so low that this control limit seems to be a reasonable threshold to distinguish between random variations and assignable variations.

The mean penetration depth is plotted for consecutive sets of armor packages. If, over a period of time, we see a drifting toward the control limit, the process can be examined and adjusted. This might possibly eliminate some future rejection of an entire lot.

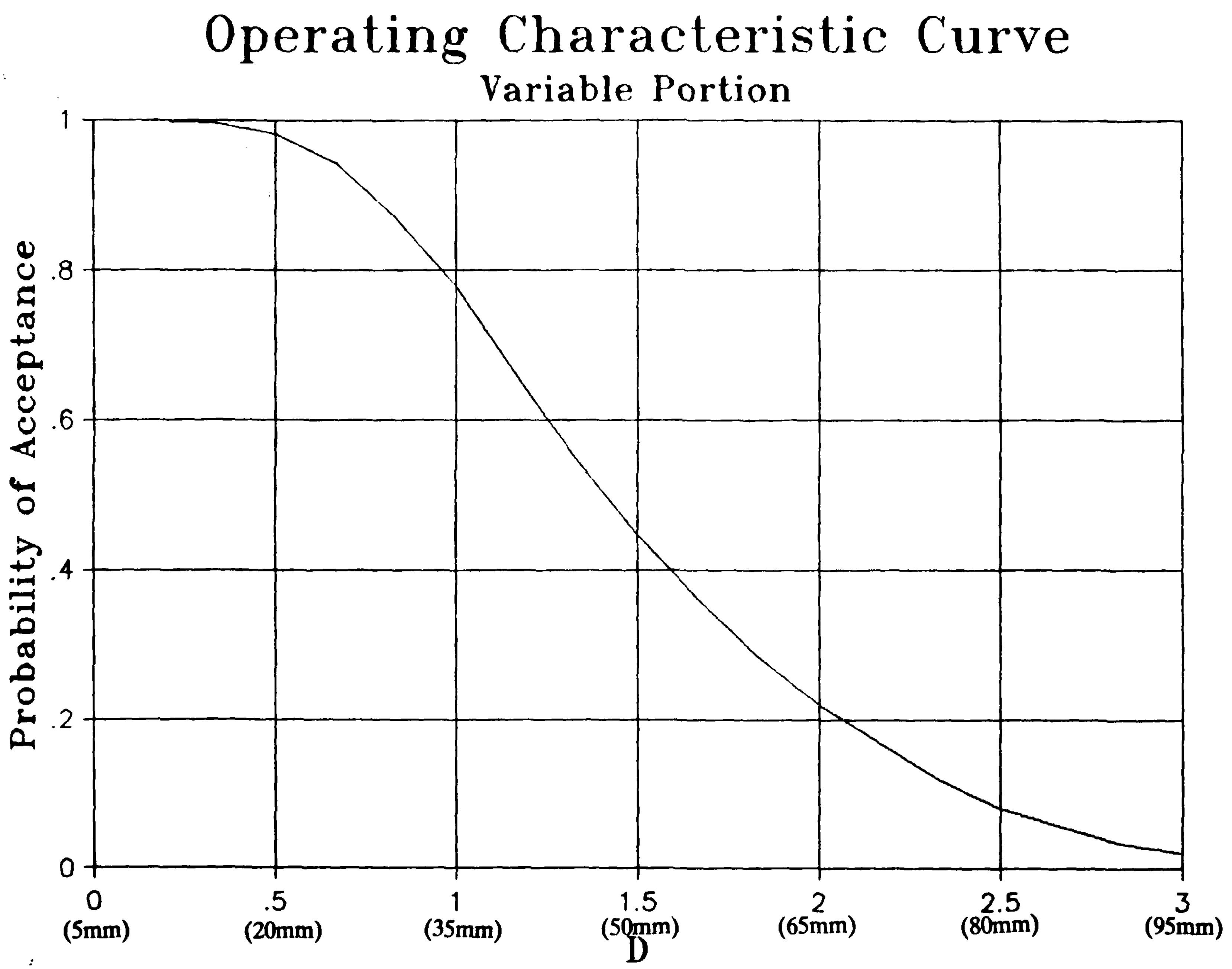

FIGURE 3. OC Curve for Variable Portion of Chain Sampling Procedure.

TABLE 4. Values of the Cumulative t-Statistic.

Degrees of Freedom (n-1)	$(1-\alpha)$ - level 0.95	0.99
3	2.35	4.54
4	2.13	3.75
5	2.02	3.37
6	1.94	3.14
7	1.90	3.00
8	1.86	2.90
9	1.83	2.82
10	1.81	2.76
11	1.80	2.72
12	1.78	2.68
13	1.77	2.65
14	1.76	2.62
15	1.75	2.60
16	1.75	2.58
17	1.74	2.57
18	1.73	2.55
19	1.73	2.54
20	1.73	2.53
21	1.72	2.52
22	1.72	2.51
23	1.71	2.50
24	1.71	2.49
25	1.71	2.49
26	1.71	2.48
27	1.70	2.47
28	1.70	2.47
29	1.70	2.46
30	1.70	2.46
31	1.70	2.45

*This table is abridged from Tables of the Probability Integral of the Central t-Distribution by R.E. Mioduski, BRL Technical Note #1570, August 1965.

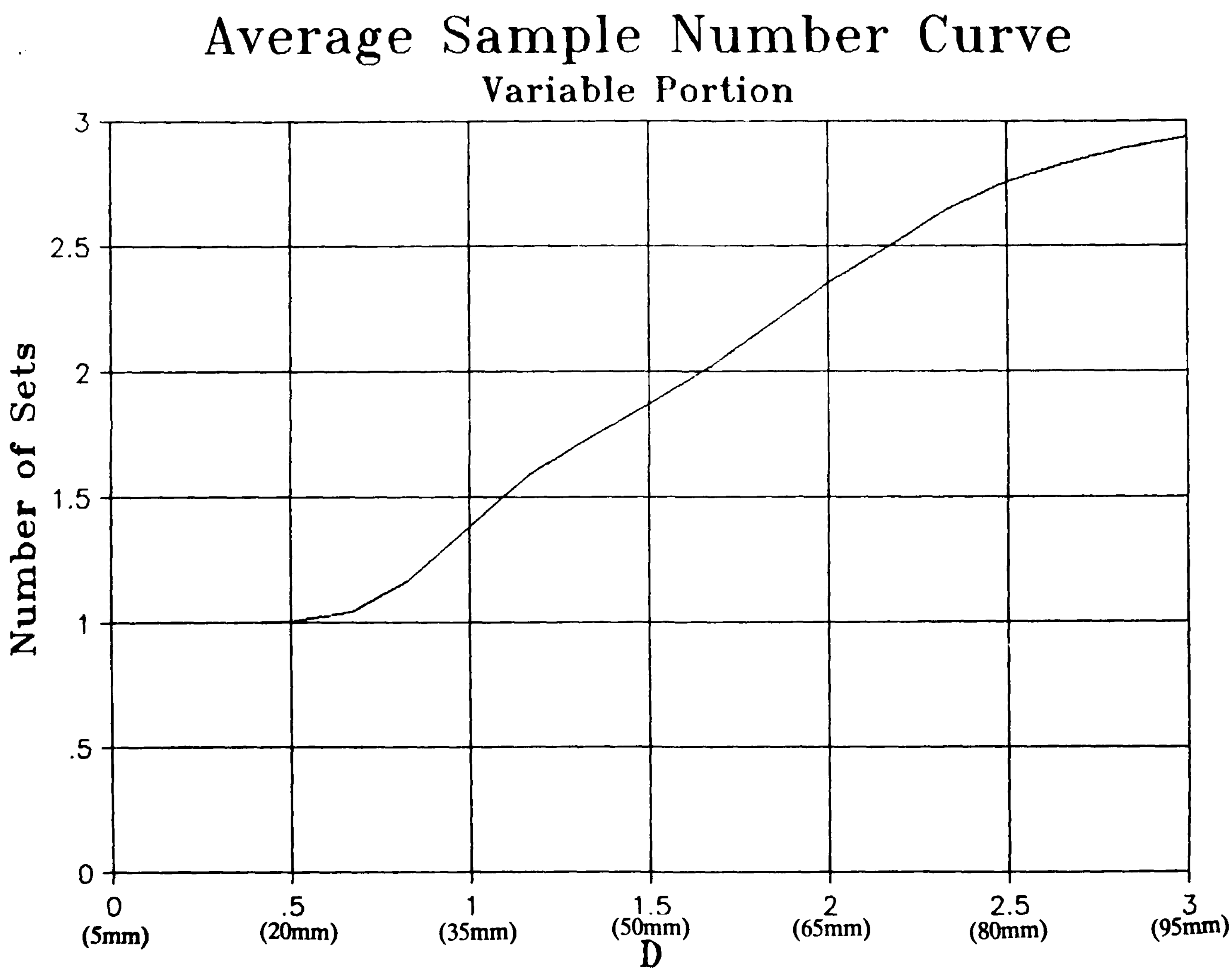

FIGURE 4. ASN Curve for Variable Portion of Chain Sampling Procedure.

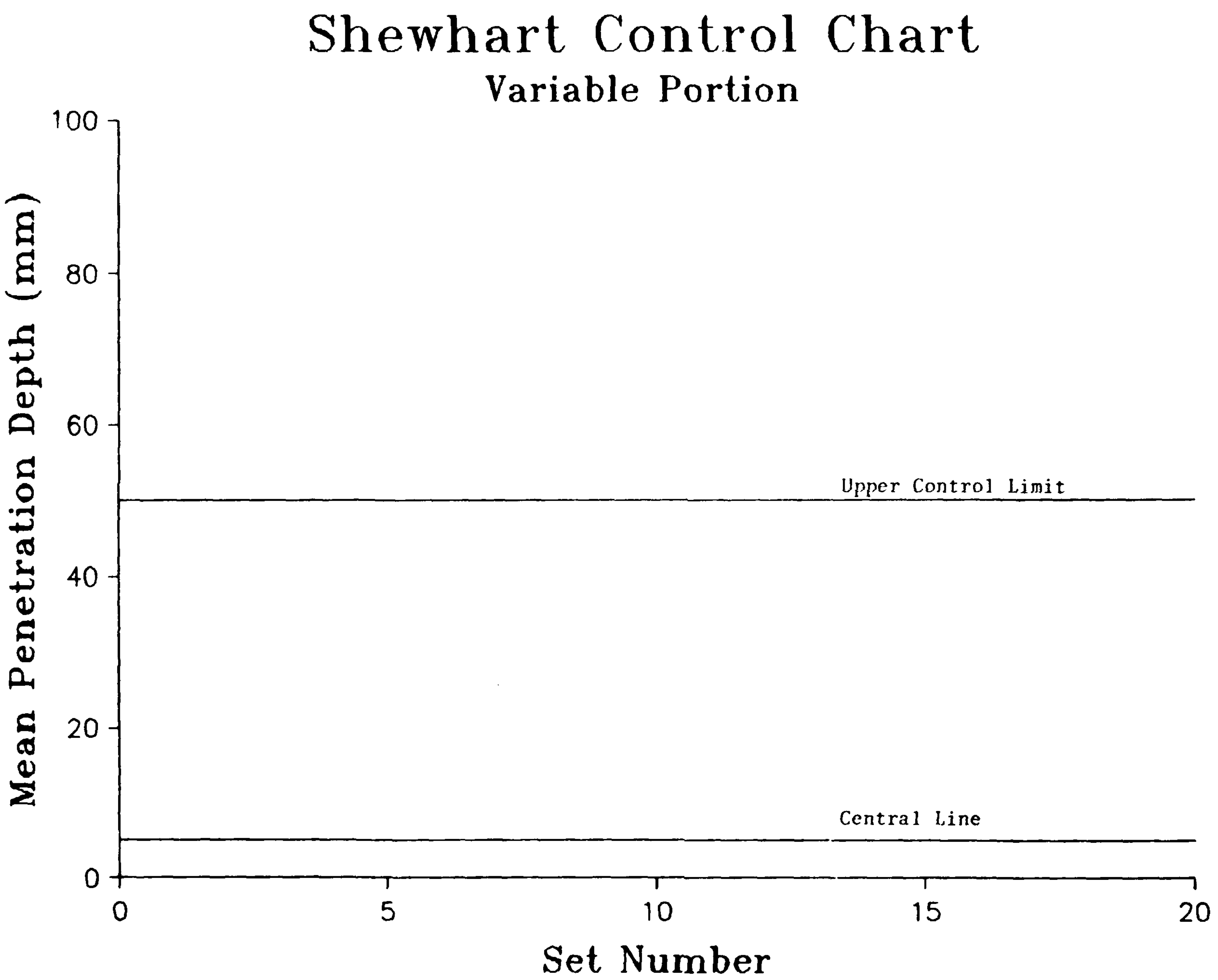

FIGURE 5. Quality Control Chart for Mean Penetration Depth.

A similar chart should be constructed for the range of penetration depth within the sample, to insure that the variability of the armor packages is not increasing. A third chart for structural integrity, the attribute of interest in our acceptance sampling plan, would also be useful. In each case appropriate upper control limits must be established.

Over the years alternative quality control charts have emerged, each with their own set of advantages and disadvantages. One of the most popular has been the cumulative sum control chart (cusum chart). Here, decisions are made based on all the data rather than just the last sample. An advantage of the cusum chart is that it often displays sudden and persistent changes in the process mean more readily (that is, with fewer samples and less expense) than a comparable Shewhart chart. However, control limits are somewhat less intuitive and, therefore, more difficult to establish. Somewhere in between the Shewhart chart and the cusum chart are quality control charts that use some, but not all, of the past data. Many of these techniques incorporate a weighting factor, providing more weight to the most recent data.

It is important that some type of quality control charts be represented in the overall acceptance sampling plan. They are relatively easy to maintain and might provide early warning signs which could be beneficial to both the producer and the consumer.

IV. SUMMARY

Generally, it is not feasible for a consumer to inspect every item from a production lot that he might want to purchase. A judicious choice of an acceptance sampling plan will allow him to sample the production lot and determine with a pre-established level of confidence whether or not it meets his specifications. Chain sampling is a particular method of lot acceptance sampling used when sample sizes are small. It utilizes the most recent information over the past history of production lots to provide more confidence in the decision.

In testing armor packages for acceptance by the US Army, chain sampling provides a logical method, since destructive testing dictates small sample sizes. A technique involving both structural integrity (attribute sampling) and penetration depth (variable sampling) has been proposed. A right-side armor package and a left-side armor package constitute one set. The procedure allows for accepting the production lot (one month's production) after examining just one set. It allows for rejecting the production lot only after testing at least two sets. There is a region of no decision; but after the chain has reached its maximum length of eight sets. a decision will always be rendered.

Operating characteristic curves provide the probability of accepting lots given a percent structurally defective (attributes) and given a mean penetration depth (variables). Average sample number curves provide the expected sample sizes necessary to make such decisions.

In addition to the acceptance sampling plan, control charts should be used for both the attribute and variable parameters. These charts display sample results for particular parameters such as percent defective, mean penetration depth, and variability of penetration depth. The data might be presented as the sample values or as sums over a preceding number of samples. By continually examining the control charts, we can see when one of the parameters

is drifting toward the rejection region, enabling the producer to make adjustments and, possibly, preventing rejection of an entire lot of armor packages.

The proposed lot acceptance sampling plan was briefed to the Project Manager M1A1 on 14 April 1988 at Aberdeen Proving Ground, Maryland. It was approved and will be adopted subject to any refinements agreed upon by both the US Army Ballistic Research Laboratory and the Project Manager.

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